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Toward User-Friendly Robotic Assistance for Enhancing Accuracy and Safety of Reconstructive Microsurgery

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Abstract— **Reconstructive microsurgery enables extraordinary procedures such as breast reconstruction, face allograft, or torn member saving. However, several gestures require a precision that goes beyond human dexterity. An ergonomic robotic assistance is being developed to push back the current frontiers of microsurgery and scale it down to the sub-millimeter scale of so-called super-microsurgery. The robot would be integrated transparently and intuitively into standard procedures performed under a microscope, so as to make super-microsurgery safer with limited additional cost.**

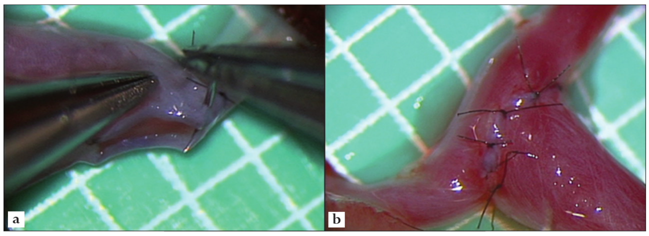

Fig. 1. Microanastomosis on graph paper (from [1].)

I. Context and Objectives

Since the first vascular anastomosis (see Fig. 1) defined at the beginning of last century by A. Carrel, important advances have been made in microsurgery: Tissue autograft, face allograft, torn member saving, hand surgery, etc. None of this could be performed without several major technological innovations such as operating microscope that offers up to 50x magnification [1] and the adaptation of instruments and suturing wires, whose diameter may be smaller than 15 μm. However, several gestures require a precision that goes beyond human dexterity [2], [3]. For this reason, microsurgery procedures such as free flap reconstructions are extremely challenging and remain not very widespread. In particular, the DIEP (deep inferior epigastric perforator) [4] is a complex surgical act of breast reconstruction that consists in removing a vascularized skin flap (with fat tissue) from the patient's lower abdomen, and transplanting it on the breast after a tumor resection (see Fig. 2). At the moment, this procedure requires to cut deeply into the abdominal muscles and to remove a piece of rib from the chest to access blood vessels large enough to be anastomosed. The poor accessibility of the deep surgical sites and the high accuracy required restricts the use of this promising technique in surgical routine. Providing surgeons with a device to assist them in performing safely microanastomoses on sub-millimeter vessels closer from skin could decrease invasiveness of DIEP and other free flap reconstructions, and make these surgical procedures feasible by most microsurgeons.

A couple of exploratory studies with the Da Vinci surgical system (Intuitive Surgical, Inc.) showed feasibility and highlighted the benefits of robotic assistance for very delicate microsurgery gestures [5], [6]. This teleoperated system allows a motion downscaling and decreases tremor magnitude. However, the Da Vinci system is expensive to purchase and to use. It is also very cumbersome and takes the surgeon away from the operative field. Image magnification provided by the stereo-endoscope might not be sufficient for microsurgery. Furthermore, its kinematics is primarily dedicated to intra-abdominal minimally invasive surgery, and is not really suitable for open microsurgery. Finally, instruments developed by Intuitive for microsurgery are much larger and cumbersome than manual instruments. Besides this commercial system, several research prototypes have been developed in various laboratories. A tele-microsurgery system developed at Tokyo university for open neurosurgery [7] is also efficient but shares most of the Da Vinci's limitations. The RAMS system from Jet Propulsion Laboratory is also devoted to microsurgery, and is notably smaller than aforementioned systems. Yet, no performance improvement has been observed with respect to manual surgery while operative time is doubled [8]. A master-slave system for reconstructive microsurgery has been recently developed by Eindhoven University of Technology [9] but trials with vessels are not reported yet, and because of the selected kinematics, accuracy, velocity and workspace do not appear to be sufficient for our applications.

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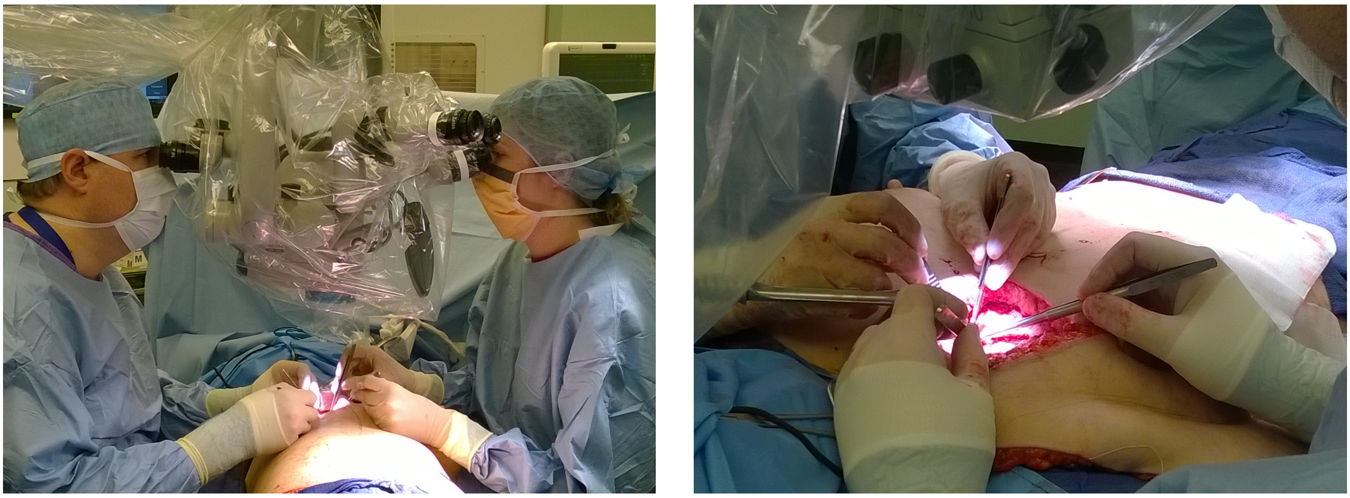

Fig. 2. Microsurgeons at work during a DIEP procedure.

Currently available teleoperation interfaces also suffer from a main limitation often raised by microsurgeons. The scaling factor is generally set constant during a gesture or even during the entire procedure. Yet, if a large reduction factor increases accuracy and decreases tremor magnitude, it also slows down gestures. In addition, the limited working range of the master arms forces surgeons to de-clutch and re-center the arms several times during some gestures (e.g. for pulling a wire over several centimeters). As a consequence, operative time is increased [7], [10], which is a common cause of non acceptance of robotic technology for surgery. This problem of procedure duration is even more severe in the particular case of free flaps, since the surgeon must perform arterial and venous anastomoses rapidly to restore blood flow in graft as soon as possible, and avoid its deterioration. Several authors therefore indicate the need for an more advanced interface allowing a variable scaling factor that could be adjusted manually or even automatically to the complexity of ongoing task [3], [6], [7], [10].

In this context, we aim at bringing both technologically and economically viable solutions to the accuracy and dexterity problems that still reserve microsurgery to few highly-skilled surgeons. Our goal is also to push current microsurgery boundaries and open the way to super-microsurgery, which requires a gesture accuracy close to 0.01 mm so as to achieve anastomoses on sub-millimeter vascular structures (thin pedicles of perforator flap, lymphatic vessels). This paper reports our current work towards the design of a robotic system for microsurgery that would be integrated easily in current microsurgery protocols. It should allow the surgeon to sit next to the patient and work under a conventional microscope. Careful attention must therefore be paid to the robot topology and dimensions, to avoid visual field obstruction while offering a sufficient workspace.

II. Instruments Motion Quantification

Workspace covered by microsurgery instruments, along with their velocity and acceleration, were recorded experimentally so as to set our robot requirements.

A. Experimental Protocol

Two microsurgeons performed a micro-anatomosis on rat adrenal aorta (1.7 mm outer diameter) from zone exposure until anastomosis permeability verification. Position, orientation, and instruments usage were recorded with three devices: (see Fig. 3):

1) A standard camcorder mounted on a tripod to analyze the global workflow and distinguish useful from unnecessary instruments motion (e.g. distinguish valid microsurgery gesture from microscope adjustment, instrument change, surgeon distraction).
2) A 3D tracking system (MicronTracker ®) to localize tip position and orientation of instruments. For this purpose, instruments were equipped with optical markers. Surgeons stated that these sensors did not change the instruments behavior and did not alter the gestures.
3) A microscope-mounted camcorder to record minute details of the surgical site.

Non-relevant instrument motions detected on camcorders recordings were excluded manually from the 3D tracking system data.

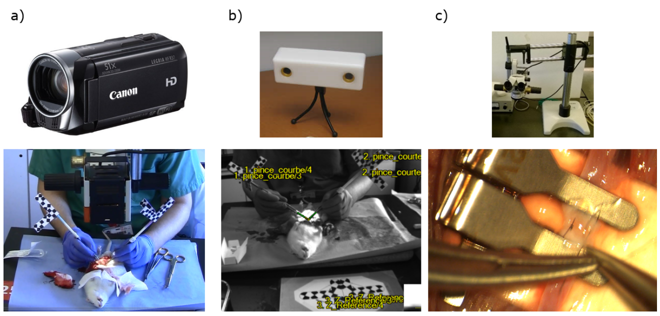

Fig. 3. Devices used for recording position, orientation, and insrtuments usage during a micro-anastomosis: a) Standard camcorder; b) 3D tracking system (MicronTracker); c) Microscope-mounted camcorder.

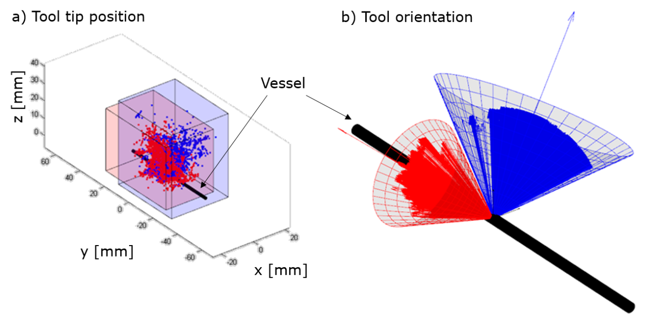

Fig. 4. Microsurgery instruments tip position and orientation with respect to anastomosis center. Surgeon is positioned on y-positive side perpendicular to vessel.

B. Results

Positions and orientations obtained are depicted in Fig. 4. Velocities and accelerations were then derived. To excluding some pick measurments assumed not to be representative only 99.9% of velocity measurements and 99.8% of acceleration measurements were taken into account. Table I gives an overview of the main results.

TABLE I

MICROSURGERY INSTRUMENTS TIP POSITION, ORIENTATION, VELOCITY, AND ACCELERATION DURING ADRENAL AORTA MANUAL ANASTOMOSIS ON RAT.

	Δ Position/Orientation	Velocity	Acceleration
x	37 mm	100 mm/s	410 mm/s^2
y	52.5 mm	100 mm/s	410 mm/s^2
z	48 mm	100 mm/s	410 mm/s^2
ψ (yaw)	135 deg	105 deg/s	570 deg/s^2
θ (pitch)	135 deg	100 deg/s	540 deg/s^2
ϕ (roll)	360 deg	125 deg/s	780 deg/s^2

III. ROBOT TOPOLOGY

Robotic assistance for improving gesture accuracy can be implemented according to two principles: comanipulation and teleoperation. Comanipulaton can filter tremors and has the advantage of being truly intuitive to use: The surgeon simply holds the instrument, as usual, and its motions are smoothed by the robot that can act in parallel such as the SteadyHand [11] or the robot developed at KULeuven [12], or be inserted serially between instrument handle and effector as in the Micron [13]. Telemanipulation, in addition, can scale motions. This feature might not be required for slow pointing tasks as in retinal microsurgery, but is likely to prove useful for more complex gestures that would remain difficult to achieve with human fingers dexterity, even with active tremor cancellation and motion damping. For this reason, the system to be designed will be based on a teleoperation architecture, although the master console should be kept as small as possible to fit on the operating table, as the system proposed in [9].

Robot needs at least 7 degrees of freedom: Six to have sufficient dexterity and the seventh to open/close manipulated tools. We decided to decouple tool tip position from orientation because accuracy requirements are very high in position ($10\mu m$) but low in orientation (in the order of 1-2 deg), where human dexterity is already sufficient. So we chose a XYZ Cartesian structure for positioning and a spherical wrist with concurrent axes crossing at tool tip, with the last rotation coincident with the self-rotation of the instrument (see Fig. 5). This kinematics can match naturally the required position accuracy and offers a sufficient angular amplitude while remaining rather compact. It has already been implemented successfully in the Robotol system [14] devoted to middle-ear microsurgery, and seems to be a good starting point for the design of our own system.

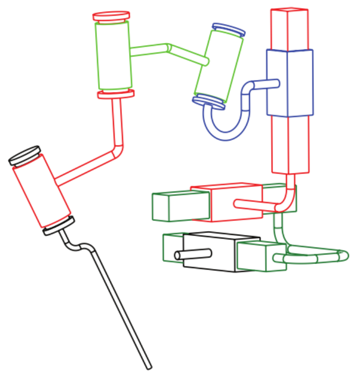

Fig. 5. Considered kinematic structure (from [14]).

IV. GEOMETRICAL AND KINEMATIC OPTIMIZATION

A. Optimization Process

Based on the specifications above, an optimization of seven geometric parameters of the wrist structure is performed. A brute force optimization algorithm tests all possible parameters combinations and checks the following criteria:

- **Constraint 1:** All positions orientations measured previously must be reachable;
- **Constraint 2:** Contact with environment must be avoided;
- **Constraint 3:** Robot cannot pass inside surgeon's visual field;
- **Objective 1:** Distance to environment should be as large as possible;
- **Objective 2:** Dexterity should be as high as possible;
- **Objective 3:** Robot must, as much as possible, leave room for an assistant surgeon to work in front of the main surgeon. This objective is reflected by maximizing the distance between the robot and the vertical plan between the two surgeons (y=0 with respect to Fig. 4). The larger the distance is the better it is.

The solutions that cannot fulfill constraints 1, 2 ou 3 are rejected while the others form the set of admissible solutions and are classified regarding their score associated to objectives 1, 2 and 3.

B. Results

200 millions of solutions were evaluated. The set of admissible solutions has got a Pareto Surface (i.e.: the sub-set comprising of all non-inferior solutions with respect to the three objectives) which is represented on Fig. 6. As depicted also on Fig. 6, the particular solution n1247 stands for a good final choice as it presents balanced scores between the 3 objectives. The robot structure corresponding to this particular solution is shown on Fig. 7.

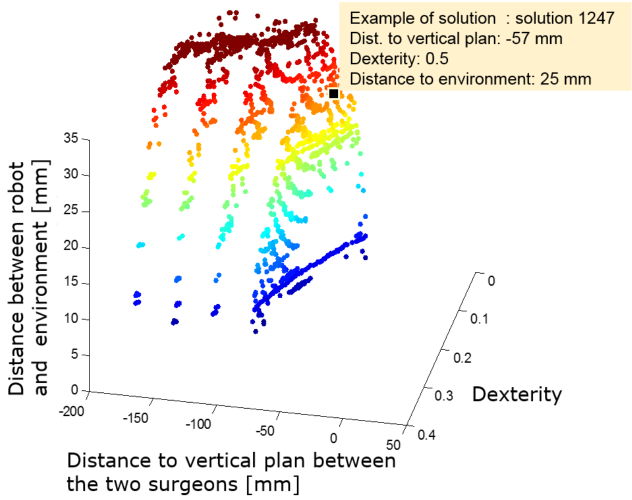

Fig. 6. Point of spherical wrist dimensions optimization Pareto surface.

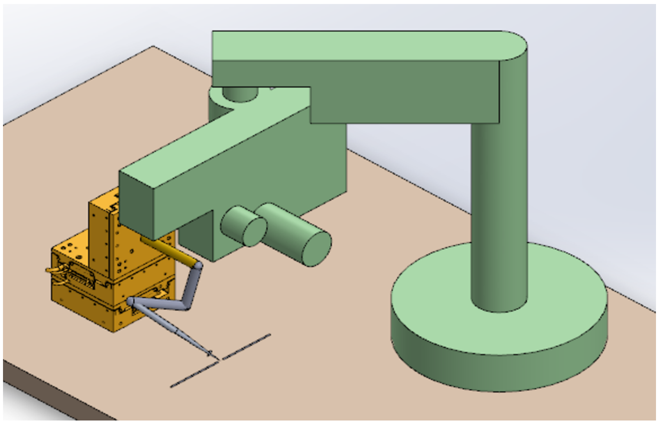

Fig. 7. SolidWorks representation of solution 1247 in its environment.

V. Conclusions and Future Work

Optimization process is still under refinement and the best solution will then be selected to offer a good balance between the three objectives. A prototype will be designed and built subsequently. Our attention will then focus on the control interface in order to make robot use as fast and intuitive as possible. As stated above, this is essential in therapeutic gestures assistance. Indeed interaction modes between surgeons and robot are a decisive factor in the system acceptance by users, as demonstrated by the large diffusion of the Da Vinci surgical system that offers a comfortable and intuitive interface, despite little evidence of its clinical interest. In particular, we'll propose different interaction modes between surgeon and robot and study their impact on system performance from the point of view of ergonomics, usability, executed gestures accuracy, and task duration.

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